

# Novel Acoustic Scattering Processes for Target Discrimination

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## LONG TERM GOALS

This is part of the Shallow-Water Autonomous Mine Sensing Initiative (SWAMSI) to improve the reliability of acoustic methods using a wide frequency range and scattering data not necessarily limited to monostatic signatures.

## OBJECTIVES

The objective of this grant is to examine issues supportive of the SWAMSI team effort by improving the understanding of acoustic scattering processes relevant to MCM and the shallow water environment. The current emphasis is on the interpretation of bistatic synthetic aperture sonar and acoustic holographic images. Other objectives involved improved understanding and modeling of scattering mechanisms that are broader in scope and are outlined below.

## APPROACH

A multifaceted research approach appears to be advisable because some acoustic strategies may not *always* be applicable and different strategies may require widely different *amounts of time* to acquire the needed data for a given potential mine field. Consequently it appeared to Marston that the SWAMSI program should retain research components that support both *low frequency* and *high frequency* sonar technologies. It would be potentially useful to understand which features of the scattering are important for discriminating between live (explosive-filled) targets and decoy targets containing other materials. Commonly used explosives have some similarity to certain solid plastics in their acoustic properties: (1) both materials have longitudinal wave speeds greater than the speed of sound in sea water, but less than rocks, cement, or metals: (2) in many cases both materials have shear wave velocities *less than* the speed of sound in sea water.

The approach has several activities. Many of these were summarized in the annual report submitted in September 2005 and 2006 [1]. The current report will emphasize the principal activities for FY2007. The selection of targets was shifted during FY2007 to allow for relevance to NSWC-UW(APL) experiments carried out in March 2007 in the NSWC Pond. These research activities in FY2007 were:

(1) **Improved apparatus for laboratory based acquisition of scattering data:** With the partial support of this grant and ONR grant N000140310583, there have been additional improvements to our 7000-gallon facility used to acquire monostatic and bistatic scattering data at Washington State University (WSU). The changes in FY2007 involve improved transducers for data acquisition. The

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14. ABSTRACT <b>The objective of this grant is to examine issues supportive of the SWAMSI team effort by improving the understanding of acoustic scattering processes relevant to MCM and the shallow water environment. The current emphasis is on the interpretation of bistatic synthetic aperture sonar and acoustic holographic images. Other objectives involved improved understanding and modeling of scattering mechanisms that are broader in scope and are outlined below.</b>					
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list of activities noted below concern tasks associated with grant N000140410075. Other ONR supported activities using this facility are reported elsewhere.

(2) **Bistatic short pulse scattering from tilted metal cylinders made of stainless steel and aluminum:** To facilitate the interpretation of scattering mechanisms, it is helpful to view the evolution of the time dependence of the echoes as a function of scattering angle and cylinder tilt angle relative to the illumination.

(3) **Bistatic synthetic aperture holographic sonar imaging:** It has been possible to form images from data acquired as noted in item (2) by the application of a back-propagation algorithm based on the methods of acoustic holography. Selected results relevant to the interpretation of Bistatic SAS images are noted in this report for tilted metallic cylinders. This algorithm was developed by the graduate student supported by this grant (K. Baik).

(4) **Bistatic SAS imaging using a conventional algorithm:** An alternative algorithm was developed by Dr. Steve Kargl at UW-APL for applications such as the SAX-04 data [2]. Dr. Kargl has kindly supplied a detailed description of his algorithm which Baik has modified for data acquired at WSU.

(5) **Monostatic scattering of transients from tilted metal cylinders as a function of orientation (tilt) of the cylinder:** These experiments were helpful for identifying ray-based scattering mechanisms relevant to activities (3) and (4) and to activities (6) and (7).

(6) **Participation in NSWC-UW(APL) experiments at the NSWC Pond:** With the partial support of this grant and grant N000140310583, Marston was able participate in aspects of these experiments. Aspects of this participation included the suggestion of physical mechanisms associated with target responses, quantitative predictions of observables based on proposed mechanisms, suggestion of target placement so as to display certain scattering mechanisms, and supplemental tank experiments at WSU using scaled targets.

(7) **Scattering by an elastic cylinder near a flat surface (tilt angle dependence):** Motivated in part by issues raised by the NSWC Pond experiments in item (6), in research partially supported by this grant (and by grant N000140310583) a new small facility was built to measure the tilt angle dependence at grazing incidence of the monostatic scattering by an elastic cylinder near a flat interface. The graduate student on this project is Jon LaFollett.

(8) **Scattering of Bessel beams by a sphere:** Relatively few exact analytical results are available for the scattering of acoustic beams by simple objects. With the partial support of this grant the scattering of sound was analyzed for a sphere centered on a Bessel beam. The progress during FY2007 concerns results for solid elastic spheres and elastic spherical shells and ray-based interpretation of aspects of the scattering. Supplemental computations were carried out using finite element methods (FEM) based on a Comsol algorithm. The emphasis was on comparison with analytical results. Dr. David B. Thiessen did the FEM calculations (partly supported also by grant N000140310583).

(9) **Monostatic scattering as a function of target exposure:** Prior research by Baik and Marston (partially supported by grant N000140310583) concerning the backscattering of a partially exposed cylinder next to a flat surface as a function of the exposure of the target was extended and prepared for publication. The experiments concerned broadside illumination and they were designed in such a way as to emphasize features present in scattering by rigid targets.

## WORK COMPLETED

In addition to the progress outlined below in the Results section, the following completed publications are noteworthy. Marston's analytical results, computational results, and ray-based predictions of the scattering of acoustic Bessel beams by impenetrable and elastic spheres were published [3,4]. Related results were presented in normal and invited talks [5,6]. The work noted in item (9) was submitted for publication [7]. In addition Baik presented aspects of his imaging results [8] and he plans to present additional results [9].

## RESULTS

Progress on the activities listed in the Approach section is summarized below:

(1) **Improved apparatus for laboratory based acquisition of scattering data:** Some results obtained using the improved system are noted below. Other results are noted in the report for grant N000140310583. One modification concerned the selection and positioning of hydrophones so as to reduce the time needed to acquire data.

(2) **Bistatic short pulse scattering from tilted metal cylinders made of stainless steel and aluminum:** In reports for FY 2006, examples were given of bistatic measurements using a horizontal scan of a hydrophone for the scattering by metal and plastic circular cylinders hung with their axis vertical. The features in the resulting images were interpreted using the methods of ray acoustics. During FY 2007, the research on this grant transitioned to investigations of the scattering by tilted horizontal metal cylinders because of relevance to NSWC Pond experiments. The typical arrangement for bistatic measurements is shown in **Figure 1**. The source emits a transient burst having a peak in its frequency content of about 205 kHz. The scanned hydrophone is configured in such a way as to minimize the response to reflections from the top and bottom of the tank while maximizing sensitivity to scattering by the horizontal cylinder. The combined system response peaks near 160 kHz. **Figure 2** gives an example of bistatic scattering data of the echo from a solid aluminum cylinder for a situation where the specular reflection from the cylinder is visible as a bright early contribution. This is followed by later weaker contributions associated with surface guided waves. These waves are described here as Rayleigh waves because of their similarity to surface-guided waves first investigated by Rayleigh in an elastic half space. The importance of this result is that there are several features present in addition to simple reflection from the cylinder and that several of these features may be identified using ray-based reasoning. In addition, as explained below, these features influence the holographic and SAS images.

(3) **Bistatic synthetic aperture holographic sonar imaging:** A method was developed for producing images from the time records recorded as explained above in (2). The basic idea is to back-propagate the sampled acoustic signal using algorithms originally developed for high-frequency acoustical holography [11]. Data is only acquired by scanning a hydrophone along a single line, but this is sufficient to provide cross-range resolution of the SAS image. Range resolution is provided by using a short tone burst to illuminate the targets and by constructing a time-evolving acoustic hologram such that the signal time relative to the arrival of the specular reflection is displayed. The relative time corresponds to an apparent relative range divided by the speed of sound. The recorded signals are processed in such a way as to use only the "supersonic" wave-number components. This was previously demonstrated by Hefner and Marston [10] to give useful information about the elastic response of targets. The importance of the holographic method is that the images may be interpreted in

terms of real (or in some cases virtual) wavefronts leaving the region of the target. This way of displaying the scattering is favorable for ease of interpretation using ray-based theories. **Figure 3** shows an example where the bright lines are associated with wavefronts leaving the target as a consequence of reflection and Rayleigh-like waves guided by the target. For the target orientation shown here these are associated with helical waves guided by the target. Such helical waves were previously modeled using quantitative ray theory [12].

(4) **Bistatic SAS imaging using a conventional algorithm:** **Figure 4** gives an example of a conventional SAS image in which the spatial location of the aluminum cylinder is superimposed as a rectangle on the image. In addition to the specular reflection and edge related features it has been possible to identify image contributions associated with waves guided by the cylinder's surface. To identify specific scattering processes that affect the SAS image it has been helpful to construct, as a function of the tilt angle of the cylinder, a movie that shows the evolution of the SAS and holographic images as a function of tilt angle. In some cases it is helpful to show the evolution of the image as a function of the position of a sliding aperture of the effective hydrophone array. In some cases it is possible to use information from SAS images to construct holographic images (and the other way around).

(5) **Monostatic scattering of transients from tilted metal cylinders as a function of orientation (tilt) of the cylinder:** Backscattering of short pulses was monitored as a function of tilt angle for the flat-ended horizontal aluminum cylinders used in the aforementioned imaging experiments. At some tilt angles the backscattering was greatly enhanced because of Rayleigh-like waves guided by the cylinder's surface. Related processes were previously investigated for tilted stainless steel cylinders [13], from which aspects of the pronounced tilt angle dependence of the backscattering by aluminum cylinders of the type used in NSWC experiments may have been anticipated. It is noteworthy, however, that features associated with helical Rayleigh-like waves on the cylinder are especially easy to observe. See **Figure 5**. Other features include meridional contributions, delayed meridional contributions from a face-crossing ray, and (for large tilt angles) contributions from a direct face-crossing ray.

(6) **Participation in NSWC-UW(APL) experiments at the NSWC Pond:** For the status of these experiments see reports by Kevin L. Williams et al., UW(APL).

(7) **Scattering by an elastic cylinder near a flat surface (tilt angle dependence):** Some of the features present in the free-field bistatic data are observable but in addition there are new features associated with the proximity of the cylinder to the interface.

(8) **Scattering of Bessel beams by a sphere:** The calculations show how to select the parameters of the incident Bessel beam in such a way so as to suppress the excitation of a given mode of an elastic sphere. In some cases this suppression increases the backscattering while in others the backscattering is decreased [4]. The result was also confirmed using by Thiessen using FEM calculations [14]. Aspects of the scattering were confirmed and/or interpreted using ray theory [3-6].

(9) **Monostatic scattering as a function of target exposure:** This research is important since even when the frequency is high there are some concerns about the applicability of ray methods because for grazing incidence there can be abrupt changes in the number of geometrically allowed rays as a function either of the exposure of the target (or of the grazing angle of the incident sound). The formulation we give allows for the calculation of amplitudes associated with given ray-like processes

but the analysis is done in such a way that sudden (unphysical) changes in the backscattering amplitude are avoided.

(10) **Other areas:** There has been other progress. Contact Marston if needed.

## IMPACT/APPLICATIONS

Our laboratory based bistatic SAS and holographic observations are potentially useful for anticipating image features present in at-sea observations. Our methods of analyzing and interpreting scattering amplitudes and images will be helpful for explaining features present either in at-sea measurements or in future FEM-based scattering calculations. For images made at WSU of softer (more penetrable) tilted cylinders, see [15]. Our results suggest efficient use of planned large-scale tests. Our measurements suggest that high-frequency acoustic signatures contain useful information about elastic properties cylindrical targets. Our analysis of the scattering by acoustic beams helps to verify FEM calculations.

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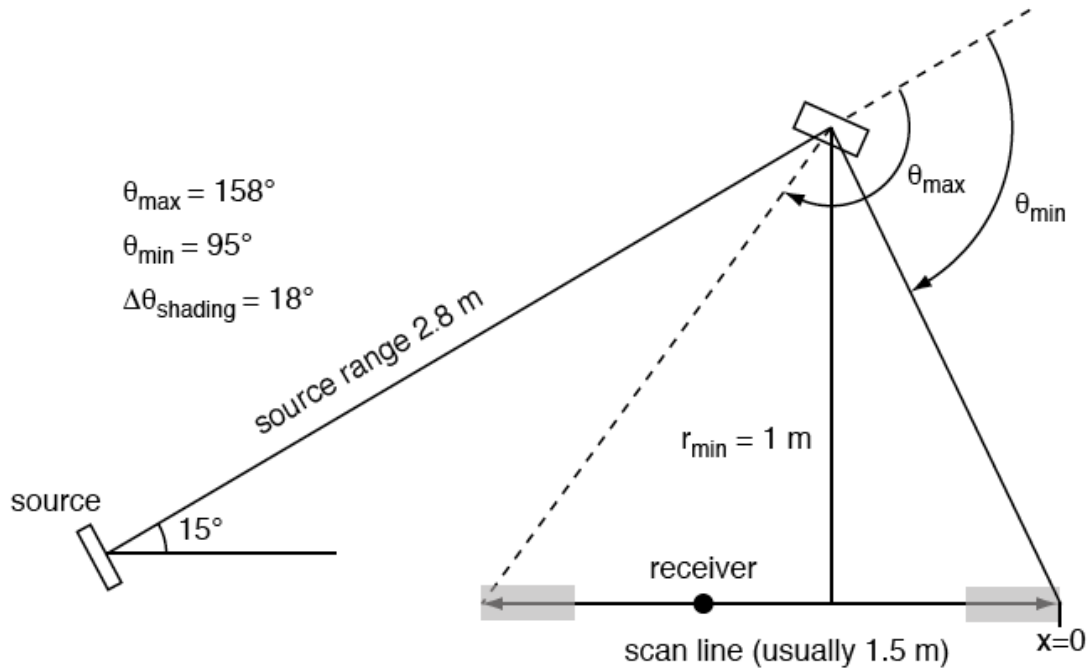
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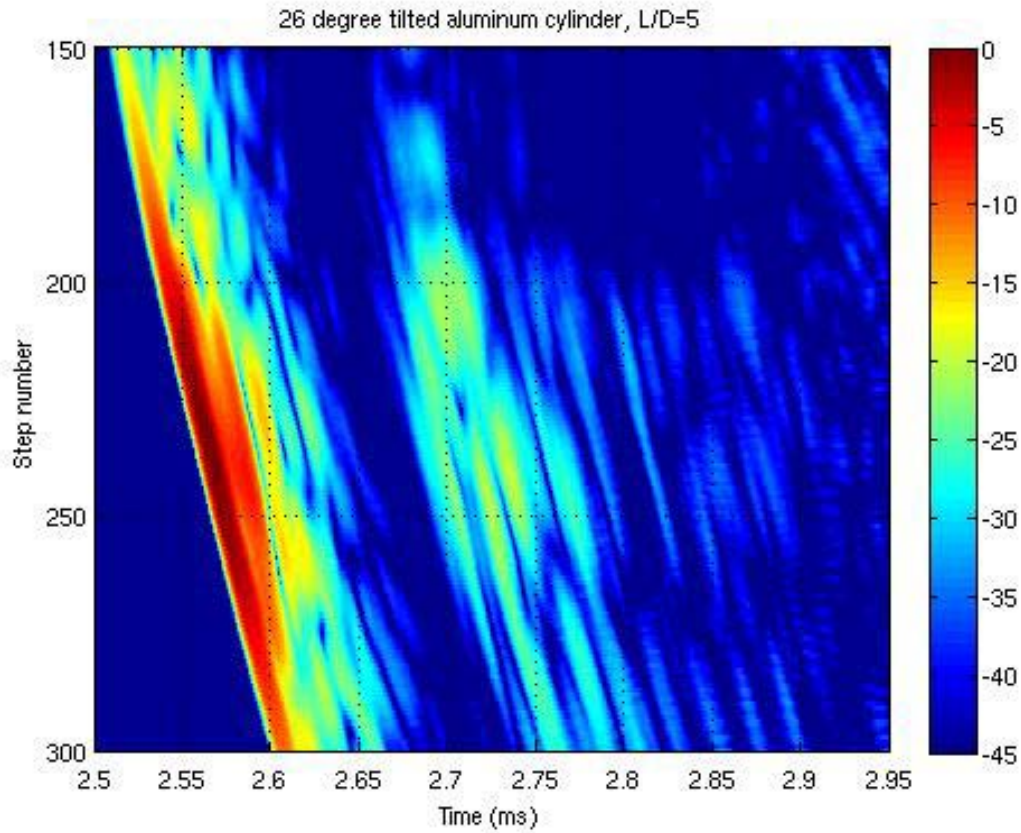
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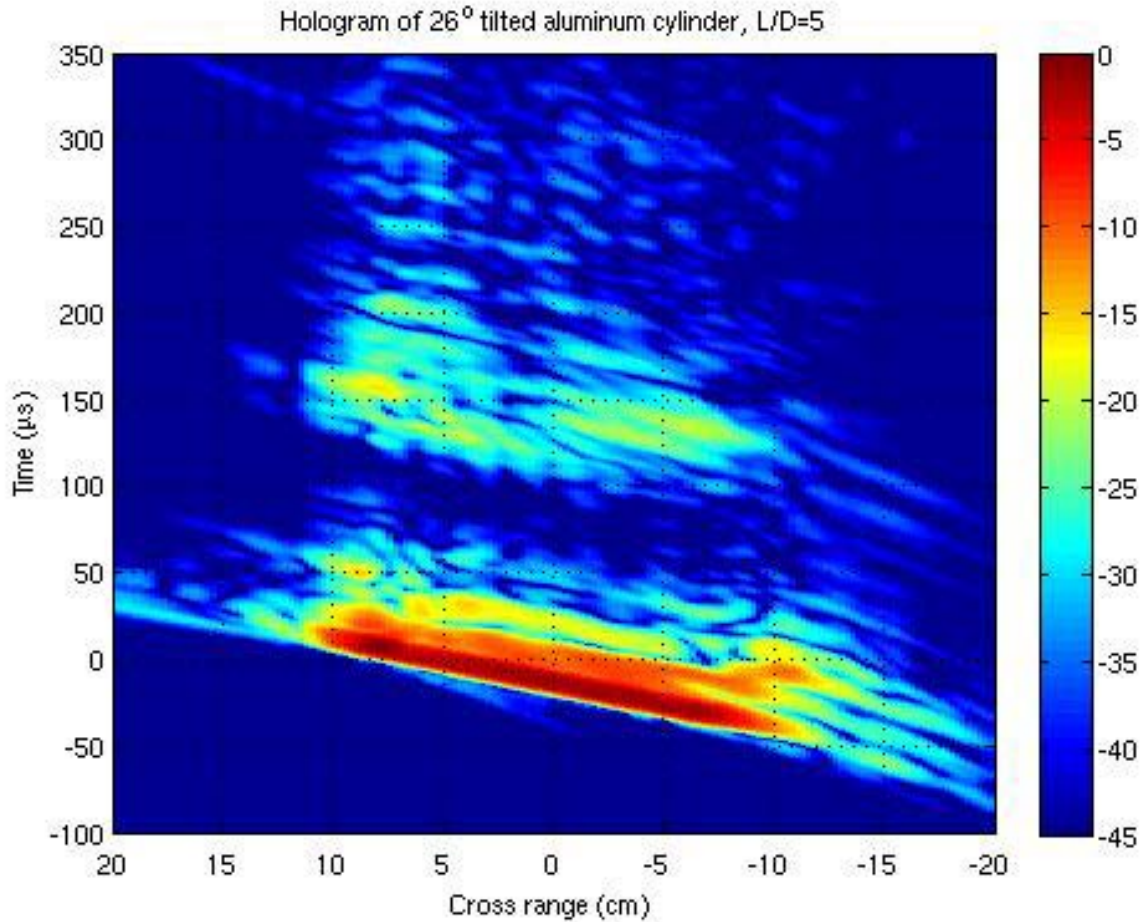


**Figure 1. Configuration used for bistatic scattering and synthetic aperture sonar measurements (viewed from above). A wide-bandwidth sound-source (lower left) illuminates the target of interest (upper right). A hydrophone is scanned along a line to record the transient response of the targets. These measurements are used to display the evolution of transient echoes and they facilitate the construction of images.**

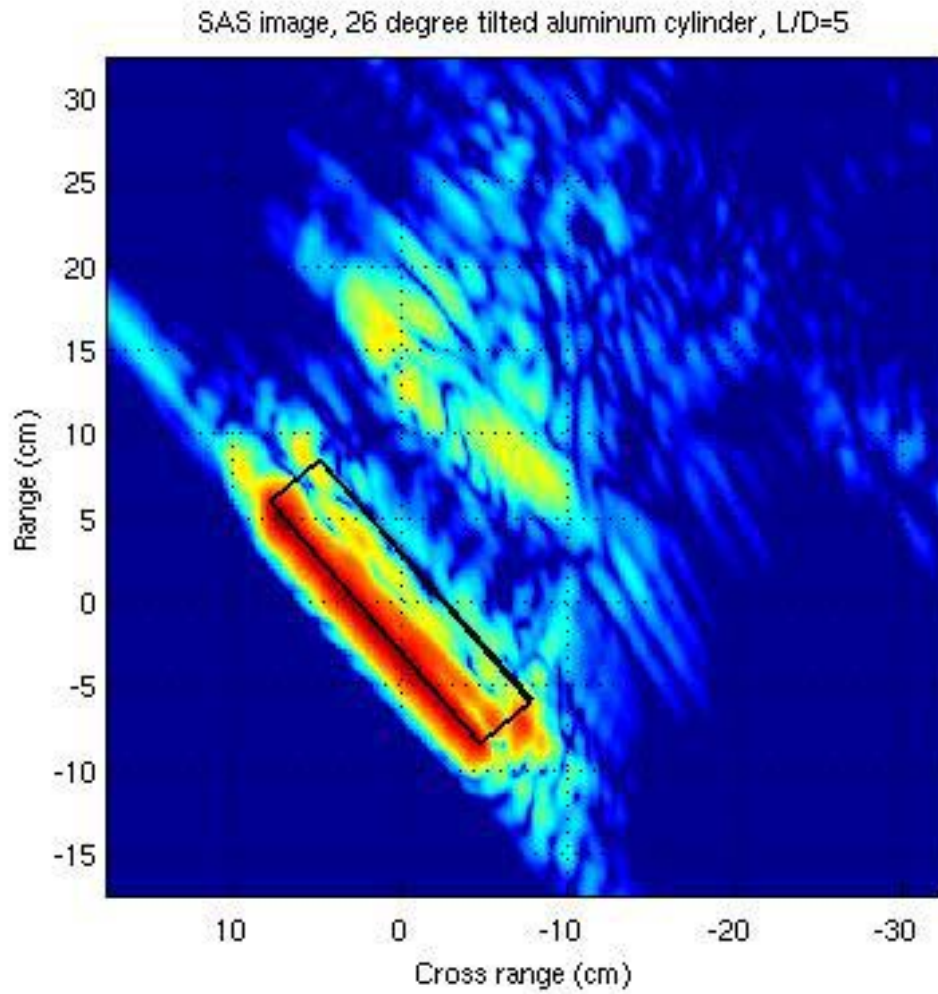


*Figure 2. Example of the evolution of the envelope of the bistatic scattering from Figure 1 in which a tilted aluminum cylinder is illuminated by a transient incident wave. The envelope of the received signal is extracted and the signal level is plotted as a color. The horizontal axis is echo arrival time from 2.5 to 2.95 milliseconds. The vertical axis is the step number and is proportional to the hydrophone displacement. Step 150 corresponds to a hydrophone near the right side of Figure 1 and in step 300 it is displaced to the left. The signal level is identified using the color bar on the right. The dynamic range is 45 db with dark red corresponding to the strongest signal and dark blue indicating a level at least 45 db below the strongest signal. Families of arcs and some of the substructure can be identified with scattered rays.*

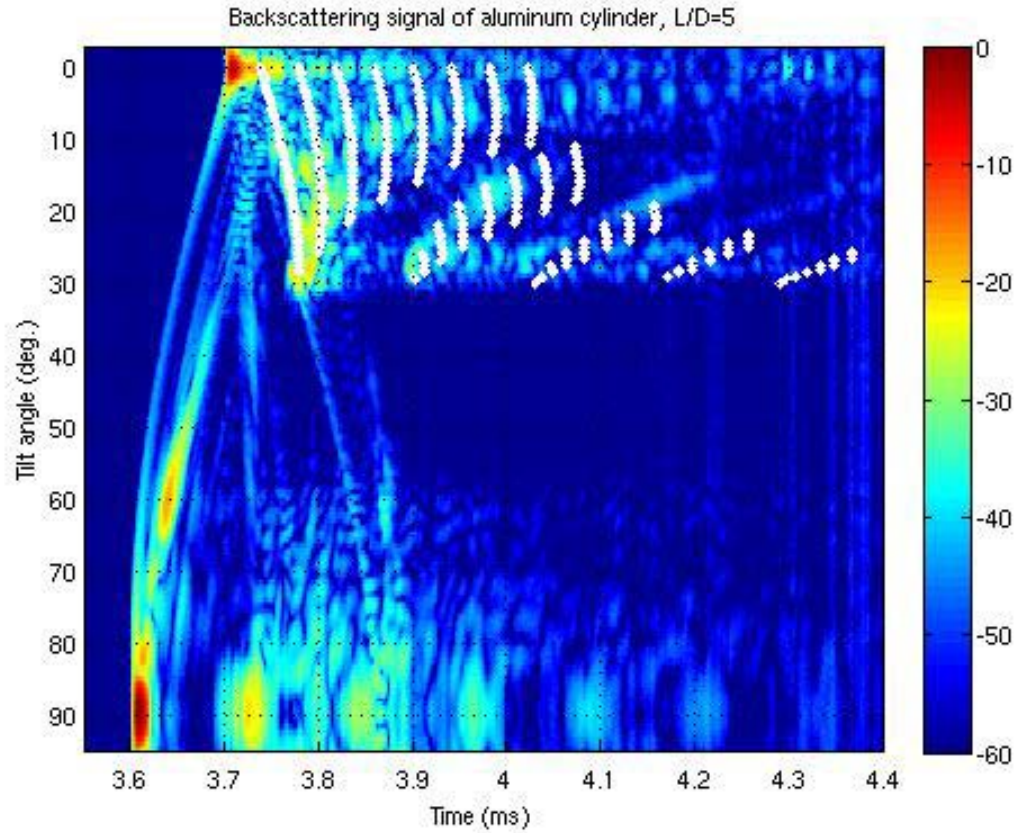




**Figure 3.** This image is constructed by holographic back-propagation to a plane near the target that is a horizontal aluminum cylinder. The image shows the time evolution of the signal crossing that plane. The horizontal axis is the cross range at the imaged region. The vertical axis is the apparent range expressed in time relative to the arrival of the specular reflection. Increasing time corresponds to greater apparent range. The signal level is plotted as a color. Families of lines and some of the substructure can be identified with scattered rays. Some of the fine features of the image are caused by helical Rayleigh waves on the cylinder that radiate sound to the scanned hydrophone. The dynamic range is 45 db with dark red corresponding to the strongest signal and dark blue indicating a level at least 45 db below the strongest signal.



***Figure 4. Bistatic SAS image for the horizontal aluminum cylinder considered in Figure 3. As in Figure 3, the horizontal axis shows cross range. The vertical axis shows the range. The location of the cylinder is indicated as a black rectangle. The brightest region is caused by the specular reflection. Some of the fine features of the image are caused by helical Rayleigh waves on the cylinder that radiate sound to the scanned hydrophone.***



*Figure 5. Backscattering of a short burst of sound by a tilted aluminum cylinder measured at WSU. The vertical axis is the tilt angle where 0 degrees is broadside and 90 degrees is end-on illumination. The horizontal axis is arrival time. The cylinder length-to-diameter aspect ratio  $L/D$  is 5. The cylinder diameter  $D$  is 38 mm. The approximate location of computed helical Rayleigh wave scattering contributions superposed as white curves. This is useful for identifying helical wave features on SAS and holographic images. This data is also useful for interpreting measurements on a scaled-up system. A db scale is on the right. The dynamic range is 60 db with dark red corresponding to the strongest signal and dark blue indicating a level at least 60 db below the strongest signal.*